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Rheological Characterization of Shale – Mud Interactions

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Abstract
In a bid to identify a best drilling fluid for a problematic oil field in the Niger Delta region, rheological tests were carried out on three mud samples; BW1, BW3 and BW4. The results affirm that the load bearing capacity of XP-07 formulated as BW3 and BW4 in this investigation is excellent and fall within the same range or even better than those of REF Mud with a more than 90% drilling success history in Niger Delta. The rheological changes of XP-07 with increase in temperature and "assimilated" microscopic shale particles are very negligible and smaller than those of REF mud. XP-07 has been strongly recommended for all drilling operations in the problematic field. It has been re-emphasised as part of our recommendations that new guidelines for the close monitoring of drilling fluids supplied by mud companies and those actually used in the field (during drilling) be put in place.

Key words: Shale – mud interactions; Rheological characterization; Niger delta

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INTRODUCTION

Mud properties are generally affected by the amount of shale "assimilated" during drilling (Akpokoje, 1994; Emofurieta & Odeh, 2007). Increase in operational temperatures and pressures with depth usually lead to changes in the rheological properties of any mud system (Emofurieta, 1999, 2001). However, the resistance to change depends on the inherent properties of the respective mud systems (Omole et.al, 1989). Satisfactory performance of a mud is sometimes aided through the use of viscosifiers a lot of which degenerate and become non-effective under higher down-hole temperatures, meanwhile operational costs are jacked up into unusually prohibitive levels (Darnley and George, 1988, Falode et al, 2008). For avoidance of this, it is professionally better to drill with muds (which are compatible with the shales and of good thermal resistance and stability (SPDC Report, 1999). The degree of influence on the properties of the mud by formation rocks which in this case are the shales is assessed by observed changes in rheological parameters such as apparent viscosity, plastic viscosity (PV), filtration loss, gel strength yield point (YP), load bearing capacity and density before and after interaction with shale under varying thermal conditions (R & D, NNPC, 1990). In this investigation, all the properties listed above (except density) were measured. The mud systems evaluated here include BW_1, BW_3 and BW_4. A reference mud (REF) was used as control and for comparative purposes.

PROCEDURE: 165 ml of the mud (previously sheared for 30 minutes) was poured into the sample cup to reach its scribe line (or liquid mark) and placed on the support plate. The support plate was then raised up until the rooter sleeve was completely immersed to its own drawn line and tightened into position with a lock and a screw.

The "apparent viscosity" of the mud as indicated by the dial reading with the sleeve rotating at 600, 300, 200, 100, 6 and 3 rpm were measured at 76°F, 120°F, 160°F, 180°F, and 200°F using a viscometer. The measurements were repeated for each of the mud systems after the addition of 10gm and 20 gm respectively of -200 mesh mildly ground Tuns shale. At the end of each run, the mud was decanted and the solid (i.e. shale) deposited at the base of the sample cup was washed with acetone, dried and weighed and expressed as a function of load bearing capacity at high temperatures. The plastic viscosity (PV) in centipoises was calculated as the 600rpm reading minus the 300rpm reading while the yield point (YP) in Ibf/100 ft^2 equals the 300rpm reading minus the plastic viscosity. The boiling temperatures of the muds and mud + clay mixtures were also recorded. The mud weight and water salinity were measured prior to commencement of the rheological readings. The results are presented in Table 1 while the graphical representations are provided in Fig.1.

Table 1
Rheological Properties from Low to High Temperature of Mud-Shale Solution

MUD CODE: BW_3
MUD WT: 9.8 PPG
RETORT: W.O.S = 36:57:7
OWR: 61/39
HPHT: 4.0 ML
WPS: 126,000 PPM
OBSN: Boils @ 220°F, evaporates @ 200°F

°F\□	80	100	120	160	180	200	220
600	112	97	80	60	56	53	47
300	79	68	57	45	43	41	36
200	67	57	48	39	37	36	32
100	52	45	39	32	30	30	26
6	26	24	21	18	17	16	14
3	24	21	19	16	15	14	13
PV	33	29	23	15	13	12	11
YP	46	39	34	30	30	29	25
YP/PV	1.39	1.34	1.48	2.00	2.31	2.42	2.27
GELS	24	21	19	16	15	14	13
ES							
SHALE: 10G OF OG + BW_3 OBSN:							
600	122	106	89	68	63	59	51
300	90	79	68	53	50	47	40
200	76	68	59	47	43	42	36
100	61	55	48	39	37	35	30
6	33	31	28	23	21	21	18
3	31	29	26	21	19	19	16
PV	32	27	21	15	13	12	11
YP	58	52	47	38	37	35	29
YP/PV	1.81	1.93	2.24	2.53	2.85	2.92	2.64
GELS	31	29	26	21	19	19	16
ES							
SHALE: 20G OF OG + BW_3 OBSN:							
600	127	114	89	68	63	58	52
300	88	78	67	52	49	45	40
200	74	66	58	46	43	40	35
100	59	53	47	38	36	34	30
6	32	29	27	22	21	20	18
3	29	27	24	20	19	18	16
PV	39	36	22	16	14	13	12
YP	49	42	45	36	35	32	28
YP/PV	1.26	1.17	2.05	2.25	2.50	2.46	2.33
GELS	29	27	24	20	19	18	16
ES			744				

MUD CODE: BW_4
MUD WT: 10.1 PPG
RETORT: W.O.S = 36:57:7
OWR: 67/33
HPHT: 3.8 ML
WPS: 285,000 PPM
OBSN: Boils @ 220°F, evaporates @ 200°F

°F\□	80	100	120	160	180	200	220
600	92	80	68	56	55	52	49
300	62	54	48	42	42	41	37
200	52	45	40	36	36	35	33
100	40	35	31	30	30	29	28
6	20	18	17	17	17	16	16
3	18	16	15	15	15	14	14
PV	30	26	20	14	13	11	12
YP	32	28	28	28	29	30	25
YP/PV	1.07	1.08	1.40	2.00	2.23	2.73	2.08
GELS	18	16	15	15	15	14	14
ES							
SHALE: 10G OF OG +BW_4 OBSN:							
600	109	92	80	64	61	58	56
300	75	65	57	48	46	45	44
200	63	54	48	42	40	40	39
100	48	43	39	34	33	33	32
6	25	23	21	20	19	19	19
3	22	21	19	18	17	17	17
PV	34	27	23	16	15	13	12
YP	41	38	34	32	31	32	32
YP/PV	1.21	1.41	1.48	2.00	2.07	2.46	2.67
GELS	22	21	19	18	17	17	17
ES							
SHALE: 20G OF OG + BW_4 OBSN:							
600	112	98	81	66	61	59	56
300	75	68	58	48	47	46	45
200	63	57	49	42	40	40	39
100	48	44	38	34	33	33	32
6	29	22	20	20	19	19	19
3	27	20	18	18	17	17	17
PV	37	30	23	18	14	13	11
YP	38	38	35	30	33	33	34
YP/PV	1.03	1.27	1.52	1.67	2.36	2.54	3.09
GELS	27	20	18	18	17	17	17
ES			833				

MUD CODE: REF
MUD WT: 10.2 PPG
RETORT: W.O.S = 36:57:7
OWR: 70/30
HPHT: 3.8 ML
WPS: 213,000 PPM
OBSN: Boils @ 220°F, evaporates @ 200°F

°F\□	80	100	120	160	180	200	220
600	110	102	87	51	48	44	40
300	66	59	49	29	28	26	25
200	50	43	36	23	22	20	19
100	33	26	22	15	14	14	14
6	9	7	6	5	5	5	5
3	7	6	5	4	4	4	4
PV	44	43	38	22	20	18	15
YP	22	16	11	7	8	8	10
YP/PV	0.50	0.37	0.29	0.32	0.40	0.44	0.67
GELS	7	6	5	4	4	4	4
ES			329				
SHALE: 10G OF OG +REF OBSN:							
600	127	112	88	60	53	48	44
300	78	68	54	37	34	31	30
200	58	51	41	29	27	25	24
100	37	33	27	20	19	18	18
6	11	11	10	8	8	8	8
3	10	10	8	7	7	7	7
PV	49	44	34	23	19	17	14
YP	29	24	20	14	15	14	16
YP/PV	0.59	0.55	0.59	0.61	0.79	0.82	1.14
GELS	10	10	8	7	7	7	7
ES							
SHALE: 20G OF OG + REF OBSN:							
600	141	128	103	68	61	54	49
300	81	73	60	43	39	35	33
200	60	55	45	33	31	28	26
100	38	35	30	24	22	21	20
6	12	11	10	9	9	9	9
3	10	10	9	8	8	8	8
PV	60	55	43	25	22	19	16
YP	21	18	17	18	17	16	17
YP/PV	0.35	0.33	0.40	0.72	0.77	0.84	1.06
GELS	10	10	9	8	8	8	8
ES			426				

1. DISCUSSION OF RESULTS

The results are presented in Tables 1a – 1b and Figs. 1a – 1d. Generally, all the mud systems show very similar rheological characteristics. For example, the apparent viscosity, plastic viscosity, yield point and to some extent the gel of all the mud systems decrease with increasing temperature being slightly more so in the Ref. Mud than BW_3 and BW_4 as depicted by the higher gradient of the REF curve in the Apparent viscosity versus Temperature plots presented in Figure 1a. This clearly suggests that BW_3 and BW_4 are thermally more stable than the Ref. Mud. The percentage decrease in the 600 rpm of BW_3, BW_4 and Ref. Mud between the temperature range of 80°F and 220°F are 58%, 47% and 64% respectively while the corresponding decrease in 300 rpm are 54%, 40% and 62% respectively (Table 1a and Figure 1a). All the mud systems including the REF boil at between 200°F and 220°F although these boiling temperatures are expected to increase under downhole pressure conditions (Weber, 1975).

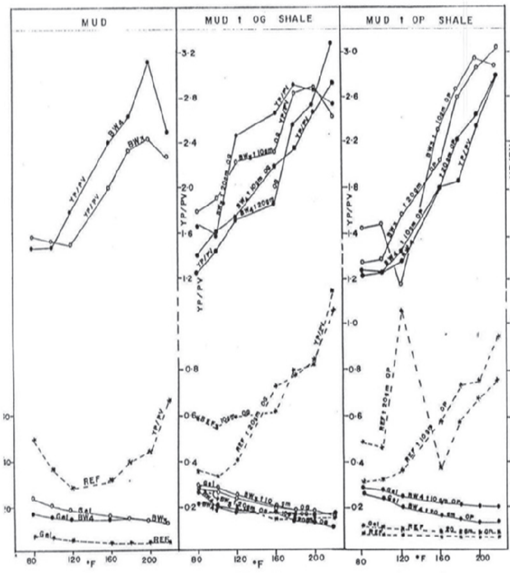

Figure 1a

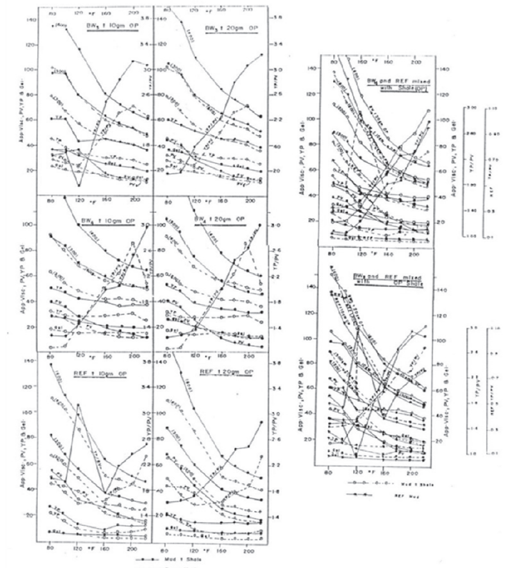

Figure 1b

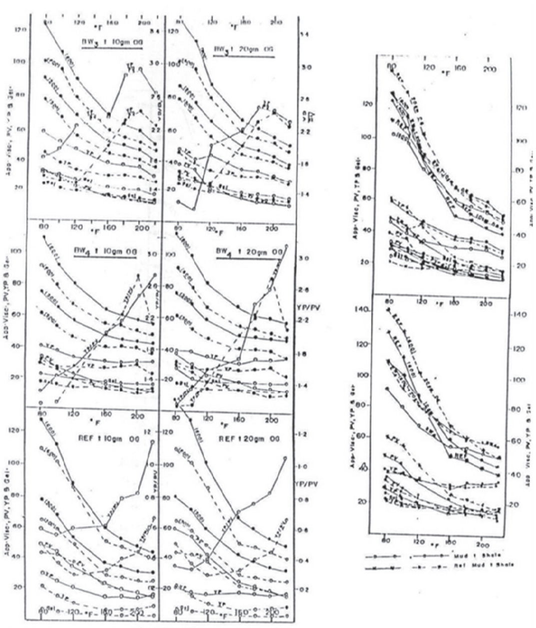

Figure 1c

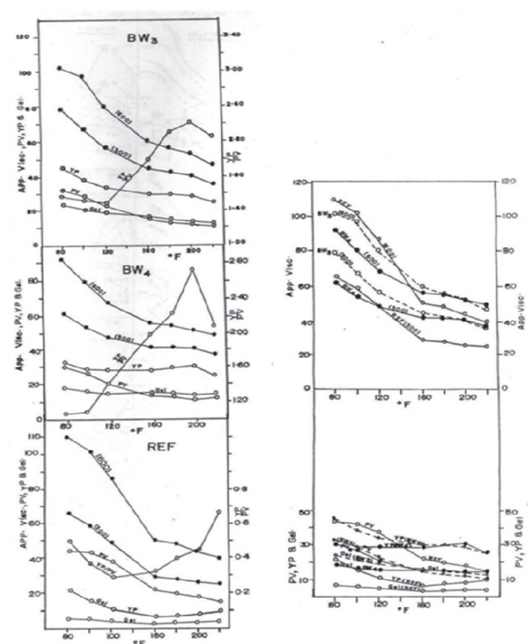

Figure 1d

Figure 1
1a. Plot of Yield Point Against Temperature; 1b. Plot of Viscosity Against Temperature; 1c. Plot of Viscosity, Yield Point and Gel Strength Against Temperature; 1d. Plot of Viscosity, Yield Point and Gel Against Temperature

Table 2
Rheological Properties from Medium to High Temperature of Mud-Shale Solution

	MUD CODE: BW_3 MUD WT: 9.8 PPG RETORT: W.O.S = 36:57:7 OWR: 61/39 HPHT: 4.0 ML WPS: 126,000 PPM OBSN: Boils @ 220°F, evaporates @ 200°F							MUD CODE: BW_4 MUD WT: 10.1 PPG RETORT: W.O.S = 36:57:7 OWR: 67/33 HPHT: 3.8 ML WPS: 285,000 PPM OBSN: Boils @ 220°F, evaporates @ 200°F							MUD CODE: REF MUD WT: 10.2 PPG RETORT: W.O.S = 36:57:7 OWR: 70/30 HPHT: 3.8 ML WPS: 213,000 PPM OBSN: Boils @ 220°F, evaporates @ 200°F						
°F\	80	100	120	160	180	200	220	80	100	120	160	180	200	220	80	100	120	160	180	200	220
600	112	97	80	60	56	53	47	92	80	68	56	55	52	49	110	102	87	51	48	44	40
300	79	68	57	45	43	41	36	62	54	48	42	42	41	37	66	59	49	29	28	26	25
200	67	57	48	39	37	36	32	52	45	40	36	36	35	33	50	43	36	23	22	20	19
100	52	45	39	32	30	30	26	40	35	31	30	30	29	28	33	26	22	15	14	14	14
6	26	24	21	18	17	16	14	20	18	17	17	17	16	16	9	7	6	5	5	5	5
3	24	21	19	16	15	14	13	18	16	15	15	15	14	14	7	6	5	4	4	4	4
PV	33	29	23	15	13	12	11	30	26	20	14	13	11	12	44	43	38	22	20	18	15
YP	46	39	34	30	30	29	25	32	28	28	28	29	30	25	22	16	11	7	8	8	10
YP/PV	1.39	1.34	1.48	2.00	2.31	2.42	2.27	1.07	1.08	1.40	2.00	2.23	2.73	2.08	0.50	0.37	0.29	0.32	0.40	0.44	0.67
GELS	24	21	19	16	15	14	13	18	16	15	15	15	14	14	7	6	5	4	4	4	4
ES																					
	SHALE: 10G OF OG + BW_3 OBSN:							SHALE: 10G OF OG +BW_4 OBSN:							SHALE: 10G OF OG +REF OBSN:						
600	135	133	117	81	73	67	61	131	121	100	80	73	68	65	137	113	98	64	57	51	47
300	98	97	80	63	58	54	49	91	84	71	60	55	53	52	82	67	66	37	35	32	30
200	85	84	71	56	52	48	44	76	70	60	52	48	47	46	61	49	41	28	27	25	24
100	69	68	58	47	44	41	37	59	55	48	42	40	39	39	37	31	26	19	18	18	17
6	40	39	35	29	27	25	23	31	30	27	25	23	23	22	9	8	8	7	7	7	7
3	37	37	32	26	24	23	20	29	28	25	22	21	20	20	8	7	7	6	6	6	6
PV	37	36	37	18	15	13	12	40	37	29	20	18	15	13	55	46	32	27	22	19	17
YP	61	61	43	45	43	41	37	51	47	42	40	37	38	39	27	21	34	10	13	13	13
YP/PV	1.65	1.69	1.16	2.50	2.87	3.15	3.08	1.28	1.27	1.44	2.00	2.06	2.53	3.00	0.49	0.46	1.06	0.37	0.59	0.68	0.76
GELS	37	37	32	26	24	23	20	29	28	25	22	21	20	20	8	7	7	6	6	6	6
ES			881							785							364				
	SHALE: 20G OF OG + BW_3 OBSN:							SHALE: 20G OF OG + BW_4 OBSN:							SHALE: 20G OF OG + REF OBSN:						
600	151	138	110	85	77	71	63	165	150	121	88	80	74	70	157	132	104	67	60	55	50
300	106	97	81	65	61	57	51	114	104	85	66	62	58	56	89	75	60	41	38	35	33
200	90	82	70	58	54	48	45	94	87	72	58	54	52	50	66	56	46	32	30	28	27
100	72	66	57	48	45	38	36	74	67	58	48	45	43	42	41	36	30	22	21	21	20
6	40	38	34	29	26	24	23	39	37	33	29	27	26	26	12	11	10	9	9	9	9
3	37	35	32	26	24	22	20	36	34	30	26	24	23	23	11	10	9	8	8	8	8
PV	45	41	29	20	16	14	12	51	46	36	22	18	16	14	68	57	44	26	22	20	17
YP	61	56	52	45	45	43	39	63	58	49	44	44	42	42	21	18	16	15	16	15	16
YP/PV	1.35	1.37	1.79	2.25	2.81	3.07	3.25	1.24	1.26	1.36	2.00	2.44	2.63	3.00	0.31	0.32	0.36	0.58	0.73	0.75	0.94
GELS	37	35	32	26	24	22	20	29	28	25	22	21	20	20	11	10	9	8	8	8	8
ES			877							766							665				

Shale Effect: In Figs.1b – 1d and Table 1b- 1d, the effect of adding 10gm and 20gm of different shale powder (-200 mesh) to the mud clearly indicate differing degrees of increases in the apparent viscosity of the mud systems. At room temperatures (i.e. 80^{o}F), BW_3 shows an increase of 10 rpm (i.e.9%) for 10 gm OG and 39 rpm (i.e. 35%) for 20gm OG. 10gm OP recorded 23 rpm (21%) increase while 20gm OP increased the apparent viscosity of BW_3 by 15 rpm (13%). On the other hand, the apparent viscosity of BW_4 increased by 17 (15%) with the addition of 10gm OG. 20gm OG did not have any significant effect. With 10gm OP, there was an increase of 19 rpm (17%) and 53 rpm (47%) with 20gm OP. The apparent viscosity of the REF mud changed by 17 rpm (15%) with 10gm OG, 31 rpm (28%) with 20gm OG, 27 rpm (25%) with 10gm OP and 47 rpm (43%) with 20gm OP. At 180^{o}F, BW_3 increases in apparent viscosity are 7 rpm which is 12% with the addition of 10gm OP and 21 rpm (37%) with 20gm OP. BW_4 increases by 6 rpm (11%) with 10gm OG, 25 rpm (45%) with 20gm OP. The REF mud increased by 5 rpm (10%) with 10gm OG, 13 rpm or 27% with 20gm OG, 9 rpm (19%) with 10gm OP and 12 rpm (25%) with 20gm OP. The shales did not affect the boiling temperatures of the muds (Weber and Daukoru, 1975).

All the plastic viscosities fall within the same range and also show systematic decreases with increase in temperature. However, the yield point (YP) of REF mud are significantly lower than those of BW_3 and BW_4. Consequently, the YP/PV of the REF are generally lower than one. API requires that the YP/PV of the mud be one or greater than one normally. This disparity is explicitly demonstrated in Fig 1d and Tables 1a – 1b. The gel strengths of BW_3 and BW_4 are also advantageously higher and fall within the expected range. The above analyses obviously prove BW_3 and BW_4 as better muds than the REF. That is not to say that REF is not a good mud, rather, that BW_3 and BW_4 are better favoured by all rheological considerations (Maron, 1969).

Gel Strength: Gel Strength is the direct measurement of the load bearing capacity or the ability of the mud to hold cuttings in suspension during connections or trips as well as continuously suspend weight material in the well. Gel strengths also have direct bearing on the swab and surge pressures created while pulling out of or going down the whole with the pipe. It is a determinant of the initial pump pressure required to break circulation (Murat, 1970).

The initial 5-, 10-, 15-, 30- and 60- minute gel strengths as well as the corresponding 30- minute values were all measured. The results in respect of BW_1, BW_3, BW_4 and REF samples are presented in Table 2. The gel values are also presented in Table 1. Gel strength values of BW_3 and those of the REF samples are identical. BW_4 values are 10-35% higher than those of BW_3 and REF. BW_1 was below detection limit in all cases. This general trend is in conformity with the rheological parameters of both the pure muds as well as the mud plus shale mixtures. The above comparative analysis clearly identifies BW_4 as the best formulation.BW_3 and the REF samples are also good and would perform creditably well except to re-emphasis that BW_4 belongs to a higher class with better rheology and thixotropy. BW_1 is comparatively similar to an unweighted KCL water-base mud both of which are probably of lower grade.

Load Bearing Capacity of the Mud Systems: The relative load bearing capacities of the mud systems under investigation have already been insinuated from earlier discussions above. However, a direct estimation or measurement of the proportion of 12gm of fresh shale cuttings that can be held in suspension by the various mud samples was carried out in a dynamic state at room temperature and 200^{o}F. The results are presented in Fig.1b. BW_3, BW_4 and the REF Mud held 100% of the ditch cuttings in suspension. BW_1 (RG2) dropped nearly everything while another REF sample (RG1) held 61% of the ditch cuttings at room temperature but dropped everything at 200^{o}F.

These results tally with the respective plastic viscosities, gel strengths and the thixotropic properties of the muds in general both under ambient and down –hole conditions. The load bearing capacities of the mud are expected to be enhanced by more than 80% under the influence of the mud pumping machine. An excellent oil well drilling mud must of necessity possess relatively high load bearing capacity to enable it evacuate ditch cuttings from the well during drilling(Emofrurieta & Odeh, 2010a).Failure to do so invariably results in bottom piling/sedimentation which can lead to stuck pipe and financial losses(Emofurieta & Odeh, 2010b). To that extent, BW_3 and BW_4 are adjudged very suitable mud systems and strongly recommended for drilling operations in the troublesome oil fields.

CONCLUSION AND RECOMMENDATION

The results of the detailed investigation of the mud and mud + shale interaction of XP-07 has revealed that the mud BW_3 and BW_4 have very suitable rheological properties both under ambient and high Temperature/Pressure conditions. They are thermally more stable and less responsive to the effect of assimilated shale during drilling. Their load bearing capacities are comparable with that of the REF mud with more than 95% drilling success in Niger Delta.

Thus, XP-07 (BW_3 and BW_4) is hereby strongly recommended for use by the Oil producing company in Niger Delta drilling operations without the slightest reservation provided good drilling habits are maintained and necessary precautionary measures are taken.

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